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Biomechanical Properties of Land Based and Shallow Water Wait: A Comparative Review of Literature

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Cover Page Footnote

This original manuscript was completed by Drs. Sarah P Shultz, Wyatt H Page and Philip W Fink as well as Mostafa Yaghoubi. Each of the authors has had full involvement in the study and preparation of the manuscript; all authors have approved submission of this manuscript.

Abstract

Aquatic locomotion exercises are frequently used in rehabilitation and cross-training for land-based athletes. Hydrostatic pressure, thermal conductivity and drag force affect a person's ability to move; therefore, it is important to understand differences of biomechanical gait in water *vs* land. This review investigated biomechanical differences between shallow water and land-based exercises. PubMed, Google Scholar, SPORTDiscus and Scopus were searched; 33 studies included walking forward (27), backward (6) and running (6). Electromyographic amplitude was similar or less in submaximal intensity during aquatic gait, in comparison to on land. At maximal intensities, however, the amplitude was similar (n=5) or higher (n=4) in water than on land. Kinetic variables (i.e. ground reaction force, lower extremity joint moments) were reduced in water (about 30-35%), while kinematic variables varied between shallow water and land-based exercise. The research highlighted in this review provides a strong foundation for improving rehabilitation and research practices associated with aquatic activities.

Keywords: aquatic exercise, kinematics, kinetics, electromyography,

Introduction

The physical properties of water differ from that of air and make aquatic exercise particularly useful during situations that require a reduction in impact loading on the body. Specifically, the unique characteristics of water (buoyancy, hydrostatic pressure, drag force and temperature) can reduce the risk of injury and assist in ease of movement. These benefits are especially important for people who need to perform rehabilitative exercises under less intense mechanical load or as an active recovery while maintaining an effective range of motion. Additionally, water exercises can be used for physical conditioning and health promotion. The general fluid drag equation ($F_d = ½pAv^2C_d$) (Alexander & Goldspink, 1977) indicates that water resistance (drag force) is positively correlated to the shape and size of the projected area and velocity squared of movement in water. Thus, changes to the speed of the exercise, or implementing aquatic devices to change the effective surface area will affect the mechanical demand placed on the individual, making aquatic exercise useful for both therapeutic and conditioning purposes in different populations. Understanding of the applied biomechanics of aquatic exercises is necessary for sports medicine and performance practitioners and users in order to structure effective programs and achieve desired outcomes that are related to the unique features of movement in water.

Shallow water exercises are widely recommended to individuals who cannot be subjected to physical activities with high impact on the lower limbs (e.g. arthritis, obesity) (Yaghoubi et al., 2018). Shallow water exercises, also known as head-out exercises, are usually performed in a water depth typically at the axillary, xiphoid or hip levels. During shallow water exercises, participants propel themselves through water by pushing off of the pool floor. Thus, participants are able to maintain contact with the bottom of the pool without a need for flotation devices (Gappmaier et al., 2006). Shallow water exercises can be beneficial as the impact force on the lower limb joints can be controlled by varying the immersion level (about 20% decrease from hip to axillary level) and the speed of movement (about 40% increase from slow to fast speed) (Miyoshi et al., 2004). In addition, buoyancy reduces loading ground reaction forces (GRF_z= about 30% of body weight, GRF_x= about 9% of body weight) at impact in shallow water exercise (Haupenthal et al., 2013; Roesler et al., 2006) while increased resistance to movement (drag force) requires the subject to exert greater propulsion force than when performed as a land based exercise (Orselli & Duarte, 2011). There is a substantial volume of literature that supports the value of using shallow water exercises as a cross-training for performance enhancement in athletes and as an active recovery between competitive events (Torres-Ronda & del Alcázar, 2014; Versey et al., 2013).

Locomotive exercises, such as walking and running, are some of the most popular forms of aquatic exercise and can be performed in both shallow and deep water. However, the absence of ground reaction forces during deep water locomotion makes biomechanical comparison between similar exercises across aquatic and land conditions difficult. During land-based and shallow water locomotion, the ability to push off the ground and bottom of the pool, respectively, provides force that is not present during deep water locomotion (Masumoto et al., 2013). Thus, there is no stance phase during deep water locomotion, whereas the gait cycle in land-based and shallow water includes toe off and ground contact (Masumoto et al., 2014). Without the propulsive force provided during stance phase, muscle and joint coordination during deep water exercise may not always mimic running on land and shallow water (Killgore et al., 2006; Masumoto et al., 2013; Miyoshi et al., 2005). Therefore, it would be inaccurate to directly compare the biomechanical responses (kinematic, kinetic and muscle activity) of land-based and shallow water exercises with deep water exercises.

Due to the similarities of having a GRF phase in shallow water and over ground locomotion this review focused on the biomechanical comparison of shallow water and land-based gait with particular interest in the potential physical benefits of participating in aquatic activity. Specifically, this review highlighted how the biomechanical characteristics of aquatic activities help to create an environment that is beneficial for a variety of populations who are pursuing physical activity. Specifically, this type of exercise can be beneficial for athletes for conditioning and rehabilitation purposes, as well as an excellent exercise alternative for the elderly, obese and clinical populations (Dowzer et al., 1998;

Greene et al., 2009; Kaneda et al., 2008a). The insights gained will help the aquatic therapist, sport medicine and sport performance practitioners to better utilize appropriate aquatic exercises for patients and athletes.

Method

Search Strategy and Selection Criteria

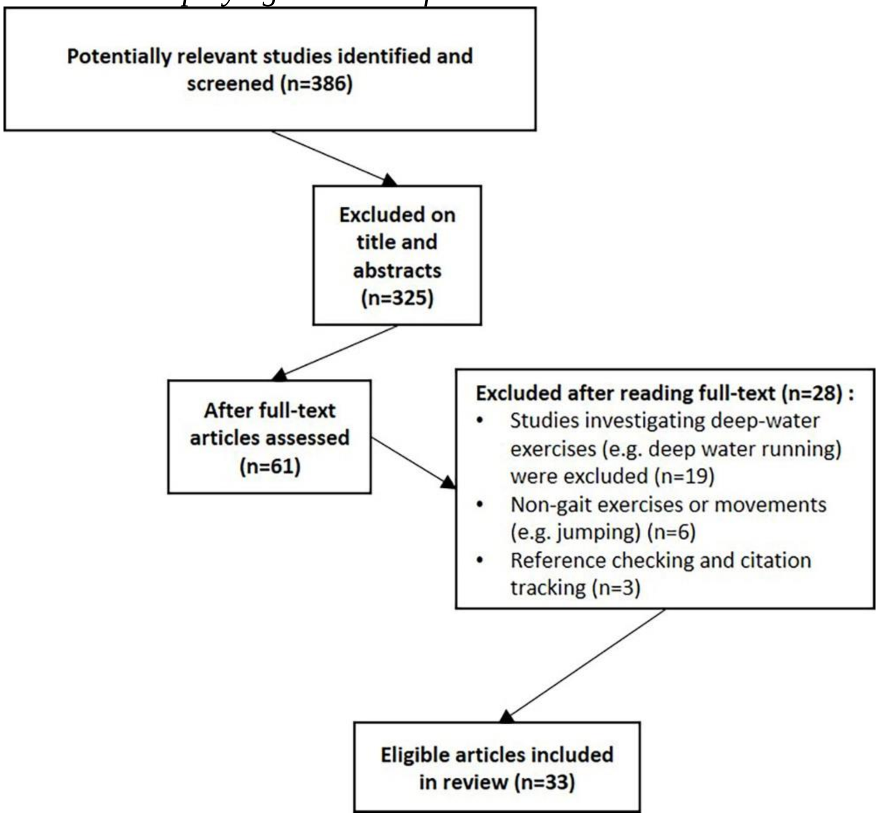
A literature search was performed in PubMed, Google Scholar, SPORTDiscus and Scopus using keywords and subject headings related to aquatic exercise, kinesiology and biomechanics of walking and running in water. In addition, articles identified through citation tracking and reference checking were examined. The studies were selected if they included a biomechanical comparison between shallow water and land-based exercise (e.g., gait). Movement was compared between shallow water and land for the following biomechanical outcomes: electromyography, kinematics, kinetics or spatiotemporal parameters. Searches were limited to articles published in peer-reviewed journals between 1992 and 2018, which are presented in Table 1. Studies investigating deep-water exercises were excluded, as the ground reaction forces were absent during deep water in comparison to land-based equivalents. Narrative reviews were included in this review of literature. Standardized mean differences (SMDs) with 95% confidence intervals (CIs) were also calculated to compare the outcomes as quantitative findings of the review using Review Manager analysis software (version 5.3, the Nordic Cochrane Centre, Copenhagen, Denmark). Effect size thresholds were classified as a SMD of small (0.2), medium (0.5), large (0.8) and very large effect (1.3) with non-significant results indicated when the 95% CI included zero (Sedgwick, 2015; Sullivan & Feinn, 2012). The literature searches identified 386 potentially relevant articles 33 studies were included in the review after titles, abstracts and full-text articles were assessed for eligibility (Figure 1).

Biomechanics of Walking in Water

Muscle Activity of Walking in Water

There has been significant interest in understanding muscle activity in varying aquatic environments (Masumoto et al., 2018; Mercer et al., 2014; Yaghoubi et al., 2015). The increase in published research is most likely due to the constant progression of water-proofing technology; laboratory equipment is now capable of being water resistant, thus allowing for real-time electromyographic (EMG) data collection under water. However, an individual's personal characteristics (age, gender, body composition, familiarity with aquatic exercise) and the testing environment (water temperature, immersive depth, exercise intensity) can vary between studies and significantly impact the EMG recordings (Cuesta-Vargas & Cano-Herrera, 2014) (Table 1). For example, elderly people display different levels of muscle activation (in particular increased amplitude of rectus femoris and biceps femoris, and a decreased amplitude of gastrocnemius) but maintain similar temporal patterns of muscle activity in comparison to young adults while walking in water (Barela et al., 2006; Shono et al., 2007).

Figure 1
Flowchart displaying selection of studies



Exercise intensity (such as walking speed or jet water propulsion) is an important contributing factor to muscle activity due to its specific relationship to the drag force which increases proportional to the speed-squared. For example, when walking is performed at self-selected walking speed and similar levels of perceived exertion, there is approximately 30% less EMG activity (Kaneda et al., 2013; Masumoto et al., 2004, 2005) and lower peak muscle amplitude (Barela et al., 2006; Barela & Duarte, 2008) in water compared to on land. However, when walking is performed at identical speeds, muscle activity was significantly higher in the aquatic environment in order to overcome the drag force (indicated by very large effect sizes, SMD > 2.78) (Masumoto et al., 2008). Similarly, when the speed of walking increases, there is a subsequent increase (12.7-17.0%) in muscle amplitude (Silvers et al., 2014). Drag force can also be increased with increased water flow, requiring subsequent increases in muscle amplitude (Silvers et al., 2014). While drag force during horizontal movement in water increases agonist muscle activity, the buoyancy force of water facilitates the vertical movement and decreases the required work of the weight-bearing and antagonist muscles (Harrison et al., 1992; Kaneda et al., 2013). The reduction of weight bearing coupled with the hydrostatic pressure on the neuromuscular system decreases the need for muscles to prepare for shock absorption at heel contact and reduced stimulation of gravity receptors within muscles in water in comparison to on land (Dietz et al., 1989; Pöyhönen & Avela, 2002). Because of the variety of potential confounding variables (e.g. water depth, locomotion speed, using underwater treadmill or shallow water), contradictory results exist for muscle activity between similar experiments in water (Table 1).

Within the trunk region, findings are least consistent in the anterior musculature. For example, Kaneda et al. (2013) found lower activity for rectus abdominis (SMD 0.30, 95% CI -0.23, 0.84) and external obliques (SMD 0.98, 95% CI 0.41, 1.56) when walking in water than over ground at slow and all speeds, most likely due to less body twisting (Kaneda et al., 2013; Kaneda et al., 2009). Other studies have found the opposite results, namely greater rectus abdominis activity at heel contact when walking at self-selected speeds in water compared to on land (Barela et al., 2006; Barela & Duarte, 2008). Because EMG findings can be strongly impacted by differences in methodology, in particular EMG normalization and walking speed, the variability in the rectus abdominis activity could be a result of these differences (Table 1). Conversely, the findings associated with erector spinae have consistently shown higher muscle activity at the end of stance to swing phase when walking at self-selected and fast speeds in the water versus on land (SMD -0.52, 95% CI -1.01, -0.02) (Barela et al., 2006; Barela & Duarte, 2008; Chevutschi et al., 2007; Kaneda et al., 2009), as postural activity is necessary to overcome drag while the trunk is propelling forward (Kaneda et al., 2013; Kaneda et al., 2009). The effect of buoyancy increases upper body instability during walking in water, which explains the measured increases in erector spinae activation to maintain a neutrally positioned vertebral column. The elevated muscle activity is further increased when walking backward in shallow water (SMD < -0.7), where water resistance would require more postural control to maintain an upright trunk (Masumoto et al., 2007b).

There have been more consistent findings within the EMG recordings of hip musculature. Gluteal muscles (maximus and medius) and tensor fasciae latae elicited higher activity when walking in shallow water compared to on land (SMD < -0.98) (Barela & Duarte, 2008; Kaneda et al., 2009). In addition, adductor longus EMG activity was also higher during the swing phase when walking in the water at fast speed (SMD -0.85, 95% CI -1.82, 0.13) (Kaneda et al., 2009). Although frontal plane motion has not been frequently studied (Costa et al., 2011), the EMG findings suggest that increases in the muscle activity of hip abductors are necessary to provide pelvic stability that is lacking when the leg is not in contact with the ground. Rectus femoris activity was higher during the entire gait cycle when walking in water at self-selected (SMD -1.34, 95% CI -2.13, -0.54) (Chevutschi et al., 2007; Kaneda et al., 2008b); moderate, and fast speed (SMD -2.25, 95% CI -3.13, -1.37) (Kaneda et al., 2007). Similarly, the biceps femoris and vastus lateralis showed higher activities during the stance phase of walking in the water at self-selected speeds (SMD < -1.60) (Barela et al., 2006; Barela & Duarte, 2008). Biceps femoris was also more responsive to changes in walking speed when walking took place in the water (Miyoshi et al., 2004). During typical gait, the majority of lower limb work is completed at the hip and within the sagittal plane (Winter & Eng, 1995). The addition of drag force occurring primarily in the sagittal plane exacerbates the demands on these muscle groups to propel the thigh forward. Although EMG studies on the thigh musculature are frequently consistent, studies by Masumoto et al. (Masumoto & Mercer, 2008; Masumoto et al., 2008) found contradicting results; specifically there was lower muscle activity for rectus femoris, vastus medialis and biceps femoris during walking in water at all speeds . However, the differences in the findings are most likely due to different testing situations (e.g. walking on underwater treadmill versus shallow water) (Table 1).

Within the shank, muscle activity of gastrocnemius and soleus decreased during plantar flexion at self-selected and moderate speeds of walking in water compared to on land (SMD > 1.51) (Chevutschi et al., 2007; Masumoto et al., 2004; Miyoshi et al., 2006). This is in contrast to other studies, which found similar or higher activity in gastrocnemius when walking in the water at self-selected speed (Barela et al., 2006; Kaneda et al., 2008b). There is greater consensus within the research on the response of ankle plantar flexors muscles to walking speed and weight loading; specifically, muscle activity of the gastrocnemius and soleus increase more when walking in water than on land when there are increases in speed and mechanical load (Miyoshi et al., 2000, 2006). There is a lack of consistent findings regarding tibialis anterior EMG activity. Some research indicated greater muscle activity for tibialis anterior in stance (Kaneda et al., 2008b) and swing phases (Barela et al., 2006) or through the entire gait cycle when walking in water, to stabilize the ankle joint against water resistance (Barela & Duarte, 2008; Kato et al., 2002). Conversely, lower tibialis anterior activity has been shown in aquatic gait (Masumoto et al., 2004), while others found no differences between the water and land environments (Kaneda et al., 2007; Miyoshi et al., 2004). The inconsistencies could be due to high variability in individuals, instruction (Miyoshi et al., 2006) and testing procedures when walking in water (Table 1). In summary, the shank muscles indicated greater EMG amplitude at maximal speeds on land compared to in water. The change in muscle amplitude could be due to greater landing forces on land and the reduction to maximal speed of walking in water due to drag forces. When considering the purpose of the aquatic exercise, practitioners must consider the effect of gait speed on muscle functionality and adjust accordingly.

Kinetics of Underwater Walking

There are conflicting reports of changes that occur to kinetic and kinematic gait parameters during walking at different speeds in water in comparison to on land. The variability in results is most likely a consequence of the differences in human propulsion in the two different environments (Table 1). The propulsion on land mainly depends on the ground reaction force while the propulsion associated with gait in shallow water will be influenced by drag and buoyancy forces, as well as ground reaction force. Biomechanical research has also been conducted into GRFs during aquatic activities compared to land-based equivalents and the reliability of the kinetic gait parameters with force plate has been confirmed recently in the aquatic environment (Barreto et al., 2016).

The shape and magnitude of the GRFs were affected along all three axes (vertical, anterior-posterior, medial-lateral) during walking in water (Barela & Duarte, 2008; Miyoshi et al., 2004; Roesler et al., 2006). The GRF patterns appear more tonic (flatter) when walking in water with less variability throughout stance phase. Several studies have shown that the vertical GRF peaks (transient and active impact forces) are decreased during walking in water compared with on land due to buoyancy and possibly lower speed (SMD < -2.01) (Barela et al., 2006; Carneiro et al., 2012; Miyoshi et al., 2005). In the anterior-posterior axis, GRF remains a propulsive force during the entire stance phase of walking in water, whereas walking on land exhibits both braking and propulsive GRFs (Barela et al., 2006; Barela & Duarte, 2008; Miyoshi et al., 2004; Roesler et al., 2006). This result suggests that when walking in water, the drag force against body (and specifically against the plantar surface of the foot) could assist as a braking force to decelerate the body before heel contact and thus does not require a braking GRF. The GRF pattern demonstrates the necessity to generate a propulsive impulse that will accelerate the body at push off and overcome the drag force in order to maintain walking speed in water (Barela et al., 2006; Barela & Duarte, 2008; Miyoshi et al., 2004). The GRF components can be modified by changing the submersion level in water (Miyoshi et al., 2005), varying the walking speed (Miyoshi et al., 2006; Roesler et al., 2006), and applying additional external weight to the individual (Miyoshi et al., 2005). Previous research has shown vertical GRF to be negatively correlated with water level but positively correlated with walking speed during aquatic gait (Roesler et al., 2006). Also, it has been shown that vertical GRF is more affected by the immersion level and weight load than walking speed (Miyoshi et al., 2004) while anterior-posterior GRF was significantly increased with increased walking speed (Miyoshi et al., 2004; Roesler et al., 2006).

The supportive effects of buoyancy reduces mechanical loads on the body when walking in water, thus decreasing joint force and moments in ankle plantar flexion and knee extension at stance phase (Miyoshi et al., 2005; Orselli & Duarte, 2011). The magnitude of this reduction in ankle and knee joint moments during walking in water can be related to the level of immersion or weight load and walking speed (Miyoshi et al., 2005; Orselli & Duarte, 2011). When walking in water, there was only one peak knee extensor moment in late stance instead of the two extensor peaks that appeared in early and late stance phase while walking on land. These findings suggest the knee joint played a minimal role in weight absorption at heel contact and complement the absence of a posterior GRF when walking in water (Miyoshi et al., 2004, 2005; Miyoshi et al., 2003).

Previous studies have shown the dominant contribution of hip extensor moment throughout stance phase as a major source of propulsive force during walking in water (Miyoshi et al., 2003, 2004, 2005; Orselli & Duarte, 2011). Thus, it is not surprising that Orselli et al. (2011) observed similar moment peaks at the hip joint between walking in water and on land (Orselli & Duarte, 2011). The hip extensor moment was more sensitive to changes in walking speed than weight loads during walking in water. For example, hip extensor moment increased as the walking speed increased but there was no relation between hip extensor moment and weight loads (Miyoshi et al., 2004, 2005). Inter-joint coordination (joint moment contribution to the function of support and propulsion at the stance phase) is also modified in the water, compared to land. (Miyoshi et al., 2005; Orselli & Duarte, 2011). Because walking in water requires only one-third and one-half of the lower extremity compressive joint forces at chest and waist water level respectively, water exercises involving human locomotion incorporate large-muscle activities while minimising the joint forces (Miyoshi et al., 2005), although the degree to which this is true will be affected by the immersion level and moving velocity (Orselli & Duarte, 2011).

Kinematics of Underwater Walking

The kinematic differences that are evident between gaits in water and over land can be explained by the variations in the physical properties of both environments. For example, participants showed different body posture and segment range of motion in aquatic gait due to the water resistance (Barela et al., 2006). Specifically, participants adopted a more neutral trunk position when walking in water compared to the forward leaning position that is adopted when walking on land (Barela et al., 2006; Barela & Duarte, 2008; Kaneda et al., 2009). A number of studies did not find significant differences in the range of motion of all joints at stance phase (Miyoshi et al., 2003) or kinematic patterns of the lower extremities during walking in the water and land (Barela et al., 2006; Miyoshi et al., 2004). There are conflicting reports on ankle joint kinematics, as most authors did not find significant differences in range of motion (Barela et al., 2006; Miyoshi et al., 2004) but others have reported both decreased (Degani & Danna-dos-Santos, 2007) and increased ankle range of motion (Kaneda et al., 2008b) during aquatic gait at self-selected speed and xiphoid-depth. Differences in kinematic patterns seem to be more consistent with increased plantar flexion at the end of stance phase and throughout swing phase during walking in water at the xiphoid process with self-selected speed (Barela et al., 2006; Cadenas-Sanchez et al., 2015; Degani & Danna-dos-Santos, 2007). Some literature has also reported increased dorsiflexion at the middle of stance phase (Kaneda et al., 2008b; Miyoshi et al., 2003, 2004). These results would suggest that higher variability of ankle joint motion may be due to different walking technique, speed and the level of immersion, which also explains the variability between studies in dorsiflexion muscles (Table 1).

Knee kinematic patterns and range of motion were roughly similar during walking in water and land (Barela et al., 2006; Barela & Duarte, 2008; Cadenas-Sanchez et al., 2015; Degani & Danna-dos-Santos, 2007) except when aquatic walking speed has been increased to match the speed selected over ground; in this case, knee joint range of motion was significantly greater (about 7° higher) in water than land (Kato et al., 2001) and at higher stride frequencies in water (Cadenas-Sánchez et al., 2016). During stance phase, several studies reported that the knee joint was more flexed at the beginning of stance phase (Barela & Duarte, 2008; Cadenas-Sanchez et al., 2015; Degani & Danna-dos-Santos, 2007; Kaneda et al., 2008b; Miyoshi et al., 2004) and throughout the stance phase during walking in water than land (Cadenas-Sánchez et al.,2015, 2016; Degani & Danna-dos-Santos, 2007). In contrast, other studies showed a more extended knee during stance phase when walking in water than land (Barela et al., 2006; Miyoshi et al., 2003, 2004) as an effect of buoyancy requiring less weight absorption, thus diminishing the required amount of knee joint range of motion and angular velocity (Miyoshi et al., 2003, 2004). During swing phase, the knee joint was also more flexed during walking in water than land in order to reduce the water resistance by reducing the trajectory area of the shanks (Degani & Danna-dos-Santos, 2007; Kato et al., 2001; Shono et al., 2007).

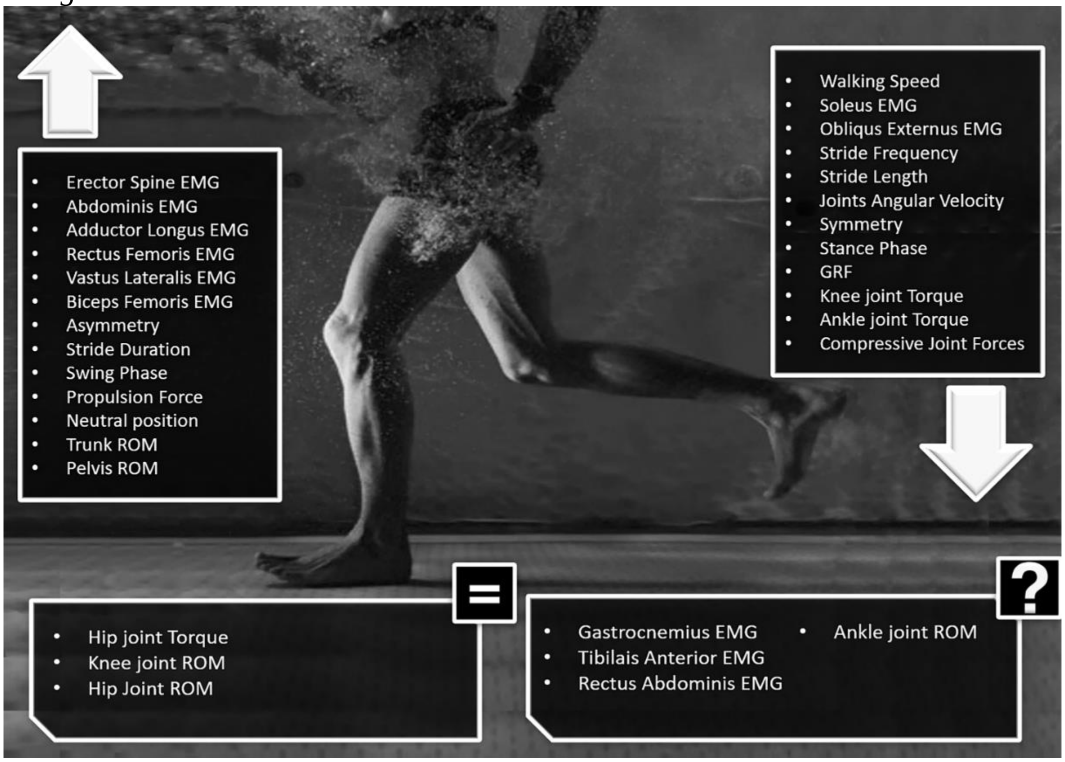
Most literature identified that the hip joint was more flexed throughout (Miyoshi et al., 2003, 2004) and at the beginning (Cadenas-Sanchez et al., 2015) and end of stance phase (Barela & Duarte, 2008; Kaneda et al., 2008b) during walking in water than on land. It was also reported that hip joint and thigh range of motion were similar at self-selected speed in water and over ground (Barela et al., 2006; Degani & Danna-dos-Santos, 2007) with increased hip kinematics during fast walking speed in water (Kaneda et al., 2009; Miyoshi et al., 2004). Trunk range of motion was also greater during walking in water than land at self-selected (Barela et al., 2006) and fast speed (Kaneda et al., 2009). Additionally, medial-lateral and vertical pelvic displacements were increased during aquatic gait (Cadenas-Sanchez et al., 2015; Kaneda et al., 2009). These results could be due to the different body posture adaptations (i.e. closer to neutral position) against water resistance and lifting force, which would be adapted to provide greater stability in water (Barela et al., 2006; Cadenas-Sanchez et al., 2015).

The physical properties of water reduced walking speed to about 50% of self-selected speed over ground (Barela & Duarte, 2008; Cadenas-Sanchez et al., 2015; Chevutschi et al., 2009; Kaneda et al., 2009). Stride frequency and length decreased (Barela et al., 2006; Masumoto et al., 2007a; Orselli & Duarte, 2011) while asymmetry between legs increased (Cadenas-Sánchez et al. 2015, 2016) when walking in water at self-selected speed. Temporally, longer stride duration (Barela et al., 2006; Kaneda et al., 2009) and swing phase (Kaneda et al., 2008b; Kato et al., 2001), as well as shorter stance phase (Barela & Duarte, 2008; Cadenas-Sanchez et al., 2015; Orselli & Duarte, 2011) were associated with walking in water.

When the speed of walking in water is set to the same speed of walking on land, the spatiotemporal relationship is altered. While stride frequency remains lower in water (Kato et al., 2001; Masumoto et al., 2007a; Shono et al., 2007), stride length and duration are now longer in comparison to walking on land (Shono et al., 2007). Despite a slower self-selected speed, lower stride frequency and length, and longer stride duration during walking in water than on land, it was recently suggested that the physical properties of water likely generated greater instability and resulted in less controlled movements and increased asymmetry (Cadenas-Sánchez et al., 2016), as well as potential changes to proprioception (Pöyhönen & Avela, 2002; Pöyhönen et al., 2002). Thus, it is important to consider the existing potential of instability, higher variability and less control of movement during aquatic locomotion for developing rehabilitation programs (Table 1 and Figure 2). Although there are still gaps in the knowledge, the lack of standardized protocols in aquatic gait research may have led to conflicting reports in the exisiting literature in aquatic gait parameters.

Figure 2

Biomechanical changes that occur when running underwater, compared to overground.



Note. Variables increased (up arrow), decreased (down arrow), remained unchanged (=), or had contradictory results (?) within the research.

Table 1
Overview studies of shallow water walking forward/backward and running.

Study	Locomotion	Mean age (SD)	Participants (n [sex])	Condition	Device	Speed instructions (Average Speed in m/s)	Depth	Main Outcomes
Barela & Duarte, 2008	walk forward	70(6) & 29(6)	Healthy elderly (10 [6M, 4F]) and adults (10 [4M, 6F])	SW & DL	NS	Self-selected (SW=0.5, DL=1.3)	X	Significantly shorter stride length and slower walking speed in SW compared to DL Significantly lower GRF_Z and increased horizontal impulse in SW than DL Significantly lower knee ROM, and increased plantar-flexion and knee flexion at the initial contact during walking in SW compared to DL
Barela et al., 2006	walk forward	29(6)	Healthy adults (10 [4M, 6F])	SW & DL	NS	Self-selected (SW=0.5, DL=1.4)	X	Significantly slower walking speed, increased stride duration, lower GRF_Z, always-positive GRF_x in SW than DL No significant differences in ankle, knee and hip ROM in SW compared to DL The EMG patterns appear more tonic (flatter) when walking in SW than DL
Barreto et al., 2016	walk forward	21(3)	Healthy young adults (49 [18M, 31F])	SW & DL	NS	Self-selected (N/S)	X	The force platform is relaiable for assessing the vertical (Fz) and antreoposterior (Fx) components of GRF during walking in SW Only positive (propulsive) values were found for GRF_x during walking in SW in comparison to DL
Chevutschi et al., 2007	walk forward	23(2)	Young adults (7 [7F])	SW & DL	NS	Self-selected (SW=0.8, DL=1.8)	H	Erector spinae and rectus femoris activities (integrated EMG) were significantly greater, while soleus activity was lower in SW Significantly reduced walking speed and stride length in SW compared DL
Degani & Danna-dos-Santos, 2007	walk forward	63	Healthy older adults (8 [N/S])	SW & DL	NS	Self-selected (N/S)	X	Not significant diferences in hip and knee ROM, but significantly lower ankle ROM and limb segmental velocity in SW than DL Increased knee flexion at the initial contact and reduced knee extension during gait cycle in SW compared to DL
Jung et al., 2019	walk forward	37(11)	Healthy adults (15 [9M, 6F])	SW	TR	Self-selected (SW=0.5)	X, W, N	Significantly increased in SL and ankle ROM, while cadence and hip ROM decreased significantly as the water depth rose during walking in SW

Kaneda et al., 2009	walk forward	25(2)	Healthy young adults (9 [9M])	SW & DL	NS	Self-selected (SW=0.3, DL=0.8), moderate (SW=0.5, DL=1.1) and fast (SW=0.6, DL=0.1.5)	X	Significantly greater %MVC of the erector spinae as the walking speed increased in SW
Kaneda et al., 2008b	walk forward	25(2)	Healthy young adults (9 [9M])	SW & DL	NS	Self-selected (SW=0.3, DL=0.8), moderate (SW=0.5, DL=1.1) and fast (SW=0.6, DL=0.1.5)	X	The %MVC of the rectus femoris was Significantly higher in SW than DL, while vastus lateralis was lower in SW than DL The lower limb joints were more flexed in SW than DL at the fast walking speed
Kaneda et al., 2007	walk forward	25(2)	Healthy young adults (9 [9M])	SW & DL	NS	Self-selected (SW=0.3, DL=0.8), moderate (SW=0.5, DL=1.1) and fast (SW=0.6, DL=0.1.5)	X	The %MVC of the soleus and gastrocnemius were significantly greater in SW than DL at different walking speed
Kato et al., 2002	walk forward	20(1)	Healthy active adults (6 [6M])	SW & DL	TR (FL)	Self-selected (SW & DL=0.4), moderate (SW & DL=0.6) and fast (SW & DL=0.8)	W	The relative integrated EMG of the tibilais anterior, gastrocnemius, vastus medialis and rectus femoris were significantly greater in SW than DL at fast walking speed
Masumoto & Mercer, 2008	walk forward	62(4)	Healthy older adults (9 [9F])	SW & DL	TR (FL)	Self-selected (SW=0.3, DL=0.6), moderate (SW=0.5, DL=1.0) and fast (SW=0.6, DL=0.1.3)	X	Significantly lower stride length and cadence in SW than DL Significantly lower %MVC of the rectus femoris, vastus meidalis, biceps femoris and gastrocnemius in SW than DL at the same speed
Masumoto et al., 2007a	walk forward	63(3) & 22(1)	Healthy older (6 [6F]) and young adults (6 [N/S])	SW	TR (FL)	Self-selected (SW=0.5), moderate (SW=0.6) and fast (SW=0.8)	X	Significantly greater %MVC of rectus femoris and biceps femoris of the older participants than younger adults, while the %MVC of the gastrocnmius was lower in older adults during SW Significantly greater cadence in older than younger adults in SW
Masumoto et al., 2004	walk forward	23(1)	Healthy adults (6 [6M])	SW & DL	TR (FL)	Self-selected (SW=0.5, DL=1.0), moderate (SW=0.6, DL=1.3) and fast (SW=0.8, DL=0.1.6)	X	The %MVC of the gluteus medius, rectus femoris, vastus medialis, biceps femoris, tibialis anterior, gastrocnemius, rectus abdominis were significantly lower in SW than DL at similar intensity
Miyoshi et al., 2006	walk forward	24(5)	Able-bodied adults (10 [6M,4F])	SW	NS	Self-selected (SW=0.5), moderate (SW=1.0) and fast (SW=1.5-2.0)	X	The averaged EMG activity of soleus was more dependednt on the load than walking speed, while the gastrocnemius activity was more dependent on the walking speed in SW
Miyoshi et al., 2005	walk forward	22(3)	Healthy young adults (16 [12M, 4F])	SW & DL	NS	Self-selected (SW=0.4, DL=0.5), moderate (SW=0.5, DL=1.0) and fast (SW=0.9, DL=0.1.4)	X	The ankle plantar-flexion and knee extension moments significantly increased with additional weight load during SW walking The hip extension moment increased significantly as the walking speed rose in SW

Miyoshi et al., 2004	walk forward	23(4)	Healthy young adults (15 [15M])	SW & DL	NS	Self-selected (SW=0.4, DL=0.5), moderate (SW=0.5, DL=1.0) and fast (SW=0.9, DL=0.1.4)	X	Only positive values were found for GRF_x, while GRF_y patterns were similar during walking in SW in comparison to DL The hip and ankle joint angular displacements were similar in SW and DL Significantly lower knee ROM and lower limb joint moments in SW than DL Significantly greater hip extensor muscle EMG activity as walking speed rose in SW
Miyoshi et al., 2003	walk forward	23(2)	Healthy young adults (8 [8M])	SW & DL	NS	Self-selected (N/S)	X	Similar lower limb joints ROM between SW and DL during stance Significantly lower joint moments at lower limb joints in SW walking compared to DL Only hip extension joint moment at the stance phase during walking in SW than DL
Miyoshi et al., 2000	walk forward	23(3)	Healthy young adults (8 [8M])	SW	NS	Self-selected (N/S)	X	Significantly greater soleus and gastrocnemius EMG activity levels as the walking speed increased in SW.
Orselli & Duarte, 2011	walk forward	24(3)	Healthy young adults (10 [4M, 6F])	SW & DL	NS	Self-selected (N/S)	X	Significantly longer stride duration in SW than DL, while stride length was similar Significantly lower angular velocity, moment, power, and compressive and shear forces in lower limb joints during walking in SW compared to DL Similar lower limb joints ROM in SW and DL
Roesler et al., 2006	walk forward	23(5)	Healthy young adults (60 [32M, 28F])	SW & DL	NS	Slow (SW=0.4, DL=0.4), and quick (SW=0.5, DL=0.7)	X & A	Significantly 20-40% of body weight lower GRF_z during walking in SW compared to DL Significantly 8-20% of body weight lower GRF_x during walking in SW compared to DL
Shono et al., 2007	walk forward	61(4)	Healthy older adults (8 [8F])	SW & DL	TR (FL)	Slow (SW=0.3, DL=0.7), moderate (SW=0.5, DL=1.0) and fast (SW=0.7, DL=0.1.3)	X	Significantly lower knee ROM and angular velocity during walking in SW than DL Significantly greater integrated EMG of the tibialis anterior, vastus medialis and biceps femoris at similar walking speed in SW and DL, while gastrocnemius and rectus femoris activities were similar
Cadenas-Sánchez et al., 2016	walking forward/backward	22(1)	Healthy young adults (8 [4M, 4F])	SW	NS	Walking forward (slow=0.6, fast=0.9), Walking backward (slow=0.5, fast=0.8)	X	Significantly lower walking speed, stride length and stance phase in SW than DL, while the asymmetry of step increased in SW Increased lower limb joints flexion at stance phase during walking forward in SW than DL

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								Increased hip and ankle flexion during walking backward in SW than DL
Cadenas-Sánchez et al., 2015	walking forward/backward	22(1)	Healthy young adults (8 [4M, 4F])	SW & DL	NS	Walking forward (SW=0.6, DL=0.9), Walking backward (SW=0.5, DL=0.6)	X	The step length asymmetry were significantly increased at faster speed in SW gait Significantly longer stance duration during walking forward than backward in SW Increased lower limb joints flexion during walking forward than backward in SW
Carneiro et al., 2012	walking forward/backward	24(3)	Able-bodied adults (22 [11M, 11F])	SW & DL	NS	Walking forward (SW=0.4, DL=1.2), Walking backward (SW=0.3, DL=0.7)	X	Significantly lower GRF_z during walking forward and backward in SW than DL Increased knee and hip flexion during walking forward and backward in SW compared to DL
Chevutschi et al., 2009	walking forward/backward	23(2)	University students (31 [16M, 15F])	SW & DL	NS	Spontaneous forward (SW=0.4, DL=1.3), Spontaneous backward (SW=0.4, DL=0.1.1), maximal forward (SW=0.6, DL=2.0) maximal backward (SW=0.5, DL=2.0)	X	The spontaneous and maximal speeds of walking forward and backward were significantly reduced in SW compared to DL for the female and male participants
Masumoto et al., 2007b	walking forward/backward	23(1)	Healthy young adults (10 [10M])	SW	TR (FL)	Walking forward and backward at slow (SW=0.5), moderate (SW=0.7) and fast (SW=0.8)	X	Significantly greater %MVC of the paraspinal, vastus lateralis and tibialis anterior during walking backward than forward on SW treadmill
Masumoto et al., 2005	walk backward	24(1)	Healthy adults (6 [6M])	SW & DL	TR (FL)	Walking backward at slow (SW=0.5, DL=1.0), moderate (SW=0.6, DL=1.3) and fast (SW=0.8, DL=1.6)	X	Significantly lower %MVC of the rectus abdominis, gluteus medius, rectus femoris, vastus medialis, biceps femoris, tibialis anterior and gastrocnemius during walking backward in SW compared to DL, with the exception of paraspinal muscles
Kato et al., 2001	walking/running forward	20(1)	Healthy active adults (6 [6M])	SW & DL	TR	Started with walking (SW & DL=0.5), gradually speed increased to running (SW & DL=3.3)	W	Significantly lower cadence and transition speed from walking (1.11 m/s) to running in SW compared to DL Significantly greater knee joint flexion as the treadmill speed increased in SW
Haupenthal et al., 2013	run forward	23(3)	Recreational athletes (20 [10M, 10F])	SW	NS	Running slow (X & H=0.6), and fast (X=0.9, H=0.7) at two immersion levels	H & X	Significantly greater GRF_z in both genders as the speed of running increased in SW Significantly greater GRF_x in males participants than females only during fast running speed in SW Significant increase in loading rate as the water level reduced in SW running
Haupenthal et al., 2010	run forward	23(3)	Healthy young adults (22 [11M, 11F])	SW	NS	Self-selected (X=0.7, H=0.9) at two immersion levels0	H & X	GRF_z corresponded to 0.80-0.98% of body weight at X & H immersion levels during running in SW respectively GRF_x corresponded to 0.26-0.31% of body weight at X & H immersion levels during running in SW respectively

Huth et al., 2015	run forward	19(1)	Healthy young adults (15 [15F])	SW & DL	NS	Running at (SW=0.9, DL=5.6)	X	Significantly lower cadence, stride length and stance phase duration, while swing phase duration was longer during running in SW compared to DL
Macdermid et al., 2015	run forward	30(13)	Competitive runners (6 [N/S])	SW & DL	TR	Running at (SW & DL=2.8)	H	Significantly lower cadence, while stride length was longer during treadmil runing in SW compared to DL Significantly reduced accelerations on impact at the heel contact in SW comapred to DL
Silvers et al., 2014	run forward	26(5)	Recreational runners (12 [12M])	SW & DL	TR	Running at 3 levels (SW & DL=2.9), (SW & DL=3.3) and (SW & DL=3.8)	X	Significantly lower %MVC of the vastus medialis and gastrocnemius, while the %MVC of the rectus femoris, tibialis anterior and biceps femoris were increased during treadmil running in SW compared to DL

Note. Condition abbreviations*:* SW shallow water, DL dry land; *Participants abbreviations:* M male, F female, N/S not specified; *Device abbreviations:* TR treadmill, FL flow-mill, NS normal surface; *Depth abbreviations:* N neck, X xiphiod, A axillary, H hip, W waist; *Main Outcomes:* EMG electromyography, GRF_z vertical ground reaction force, GRF_x anterior-posterior ground reaction force, GRF_y medial-lateral ground reaction force, ROM range of motion, %MVC maximal voluntary contraction.

Biomechanics of Running in Water

Running in shallow water can be an alternative or supplemental exercise for injury prevention, rehabilitation and recovery from sport training and competetion. Similar to walking in water, the resistive forces of water affect several temporal variables when running. Specifically, shallow water running showed significantly lower stride frequency (about 49% lower), stride length (about 70% lower), and speed (about 80% lower) (Huth et al., 2015; Kato et al., 2001) with the only similarities to running over ground occurring in stance and swing phase durations. Transition speed from walking to running also occurs at a slower speed (1.11 $m.s^{-1}$) in shallow water than on land (Kato et al., 2001). When lower extremity joint kinematics were investigated, only knee joint range of motion was significantly greater (about 20%) during running in shallow water than land at matched treadmill speeds (Kato et al., 2001). When lower extremity muscle activation was investigated during aquatic treadmill exercise at different speeds, the duration of rectus femoris, vastus lateralis, gastrocnemius, tibialis anterior and biceps femoris were increased compared to treadmill running (Silvers et al., 2014).

The buoyancy forces associated with water significantly reduce the impact forces associated with running (Huth et al., 2015; Macdermid, Fink, & Stannard, 2015). In shallow water running, the values of GRFs are affected by changes in buoyancy (the level of immersion), density (related to body composition), and resistance (speed dependant) forces (Haupenthal et al., 2013). For example, when running in shallow water at chest level, vertical GRF (0.5-0.9 BW) was lower than when the body was only immersed to hip level (1-1.2 BW) (Haupenthal et al., 2013; Roesler et al., 2006). The decreased vertical GRF means that a new source for generating a propulsive impulse is required. Thus, the anterior-posterior GRF (0.15-0.41 BW) during shallow water running was higher than stationary running in water and similar to land running (0.4-0.5 BW) (Fontana et al., 2012; Haupenthal et al., 2013; Roesler et al., 2006).

The increase in gait speed during running has a greater effect on water resistance than is seen during shallow water walking. In order to account for the large increases in water resistance, individuals modify their running technique by leaning the body forward and stronger propulsion is needed to propel the body forward, with the maximum force occuring by the end of the contact (70-80% of support phase). The gait adaptation is evident in the absence of a posterior, or braking, component of the anterior-posterior GRF curve (Dowzer et al., 1998; Haupenthal et al., 2010). Increased running speed and the level of immersion also increase the vertical and anterior GRF and range of motion, which can generate an increase in plantar flexor muscle activity (Jung et al., 2019; Kaneda et al., 2008b; Miyoshi et al., 2003). Therefore, shallow water running, despite the lower values of vertical GRF and stride frequency and absence of negative impact peak, showed similar anterior GRF with running on land (Haupenthal et al., 2013; Haupenthal et al., 2010).

Biomechanics of Walking Backward in Water

Although backward walking is not commonly performed over ground, this gait activity is often practiced in the water since the water viscosity provides postural support improving the safety of this exercise compared to on land (Becker, 2009; Carneiro et al., 2012). Backward walking in water can be a beneficial mode of exercise for patients with patella-femoral pain syndrome or hamstring strains during rehabilitation protocols, due to reduced eccentric function of the quadricps muscle (Kachanathu et al., 2013; Masumoto et al., 2005). There is more hip flexion, knee flexion, and ankle plantarflexion at initial contact when walking backward in the water compared to on land (Cadenas-Sanchez et al., 2015; Carneiro et al., 2012). There is also more ankle plantarflexion at toe-off when participants walked backward in water compared to walking backward on land. The increased plantarflexion could be a consequence of buoyancy force creating less heel contact with the floor during walking backward in water (Cadenas-Sánchez et al., 2015, 2016; Kodesh et al., 2012). However, Carneiro et al. (2012) did not find significant differences for ankle angle during backward walking between environments . When direction is considered, there is more knee flexion but less hip flexion when walking backward compared to forward in water (Cadenas-Sanchez et al., 2015; Carneiro et al., 2012).

At initial contact, the knee and hip were more flexed in water than land during walking backward and, when comparing the directions of walking (forward versus backward), the knee was more extended while the hip was more flexed during walking forward than backward in water (Cadenas-Sanchez et al., 2015; Carneiro et al., 2012). At final stance, the knee was more extended and hip more flexed during walking backward than forward in water. When comparing environments (water versus land) for backward walking, the hip was more flexed in water than on land (Cadenas-Sanchez et al., 2015) while there was no significant differences observed in the knee angle between environments (Carneiro et al., 2012). The role of the knee was further diminished in backward walking, as compressive forces at the patellofemoral joint were reduced when compared to forward walking in water (Flynn & Soutas-Little, 1993). Therefore, these results suggest that gait adaptations during walking backward in the water could be a mechanism to reduce the amount of body surface area that produces drag, in order to acheive more efficient movments (Cadenas-Sanchez et al., 2015), as well as increase vertical movements to reduce lift forces, in order to achieve greater mechanical efficiency.

Similar to the temporal differences discussed in forward walking, support phase duration is reduced when walking backward in water compared to over ground (Barela & Duarte, 2008; Cadenas-Sanchez et al., 2015). The combination of buoyancy force being applied during double limb support and the increase in drag force during swing phase could result in a diminished double limb support phase and overall reduced support phase duration (Cadenas-Sanchez et al., 2015; Pöyhönen et al., 2000). When considering direction, stride frequency was increased while stride length was decreased when walking backward in the water in comparison to walking forward in water; the differences can most likely be attributed to unfamiliarity of participants with the task (Cadenas-Sanchez et al., 2015; Masumoto et al., 2009). While there were no differences between the self-selected speeds of forward and backward walking in water, walking forward elicited higher self-selected speeds than walking backward when on land (Cadenas-Sanchez et al., 2015; Carneiro et al., 2012; Chevutschi et al., 2009). The directional differences that were prevalent on land but absent in the water can be explained by the effect of hydrodynamic properties of water (drag force, buoyancy and lower instability) (Barela et al., 2006; Cadenas-Sanchez et al., 2015; Carneiro et al., 2012; Masumoto et al., 2009). It has been suggested that the absence of a difference between directions of walking in water could be due to water resistance (Carneiro et al., 2012) and reduced maximal friction and GRFs applied to the floor surface in water (Cadenas-Sanchez et al., 2015).

Conclusions

The purpose of this paper was to provide a descriptive literature review of the biomechanical parameters of shallow water exercise in comparison to land-based equivalents. The physical properties of water have been found to increase joint range of motion while subsequently decreasing angular velocity; and reduce loading at impact, due to water-assisted body weight support. Therefore, shallow water gait can aid in the rehabilitation process by offering safe and therapeutic progression to the more common land-based protocols. Previous research has recommended that exercise in water could be a safer environment with a lessened fear of injury; however, recent studies revealed more instability, asymmetry and variability during aquatic exercises, possibly due to uncertainty in the new (aquatic) environment. Variability is specifically affected by changes in buoyancy due to immersion level and resistance forces (e.g., intensity, speed) and can affect both research and clinical applications. Therefore, the practitioner should take into consideration that the water environment is foreign for most individuals and adjust the speed and the intensity of aquatic gait to suit the needs of the individual. For example, it may be neccessary to keep the speed similar or lower during shallow water gait, particularly for rehabilitation, in order to increase an individual’s level of comfort and subsequently reduce instability, asymmetry, and variability. Despite the large number of published research studies investigating the biomechanics of aquatic activities, there is a lack of consensus in the results. Additionally, previous aquatic biomechanical research is limited to aquatic gait in adults and elderly people, but its benefits should be considered across the lifespan, and particularly for those individulas who carry excess mass (Yaghoubi et al., 2018). Biomechanical research with different types of aquatic devices (such as aqua bikes or elastic tether) for conditioning and rehabilitation purposes is also required so that practitioners can better prescribe aquatic exercise based on the appropriate intensity, water depth, technique and mode.

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